



Universiteit  
Leiden  
The Netherlands

**On the emergence of the energy transition**  
Kraan, O.D.E.

**Citation**

Kraan, O. D. E. (2019, April 25). *On the emergence of the energy transition*. Retrieved from <https://hdl.handle.net/1887/71807>

Version: Not Applicable (or Unknown)

License: [Leiden University Non-exclusive license](#)

Downloaded from: <https://hdl.handle.net/1887/71807>

**Note:** To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The following handle holds various files of this Leiden University dissertation:

<http://hdl.handle.net/1887/71807>

**Author:** Kraan, O.D.E.

**Title:** On the emergence of the energy transition

**Issue Date:** 2019-04-25

# On the Emergence of the Energy Transition

Oscar Kraan



# On the Emergence of the Energy Transition

Proefschrift

ter verkrijging van  
de graad van Doctor aan de Universiteit Leiden,  
op gezag van Rector Magnificus prof.mr. C.J.J.M. Stolker,  
volgens besluit van het College voor Promoties  
te verdedigen op donderdag 25 april 2019  
klokke 16:15 uur

door

Oscar Dirk-Jan Eduard Kraan

geboren te 's-Gravenhage  
in 1985

Promotores:

Prof. dr. G. J. Kramer  
Dr. ir. I. Nikolic

Utrecht University  
Delft University of Technology

Copromotor:

Dr. V. Koning

Utrecht University

Promotiecommissie:

Prof. dr. P. M. van Bodegom  
Prof. dr. A. Tukker  
Dr. R. Kleijn  
Prof. dr. ir. P. Herder  
Prof. dr. B. de Vries  
Dr. E. M. Fumagalli

Leiden University  
Leiden University  
Leiden University  
Delft University of Technology  
Utrecht University  
Utrecht University

This research has been funded by Royal Dutch Shell and has been carried out in collaboration with Leiden University, Utrecht University and Delft University of Technology.

Copyright © 2019 by O.D.E. Kraan

All rights reserved. No part of the material protected by this copyright notice may be reproduced or utilised in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage or retrieval system, without written permission from the author. A digital version of this dissertation is available at <https://openaccess.leidenuniv.nl/>

Cover: Designed by Bright Brands

Produced with L<sup>A</sup>T<sub>E</sub>X

ISBN: 978-94-028-1299-2

# Contents

|   |             |
|---|-------------|
| <b>List of Figures</b>  | <b>ix</b>   |
| <b>List of Tables</b>   | <b>xi</b>   |
| <b>List of Abbreviations</b>  | <b>xiii</b> |
| <b>1 Introduction</b>   | <b>1</b>    |
| 1.1 Climate change and the energy transition . . . . .  | 3           |
| 1.2 The main research question . . . . .  | 5           |
| 1.3 Research approach . . . . .   | 8           |
| 1.4 Relevance . . . . .   | 13          |
| 1.5 Aim and outline . . . . .   | 14          |
| <b>2 Intellectual framing of the energy transition</b>  | <b>19</b>   |
| 2.1 The pace and the path of the energy transition . . . . .  | 21          |
| 2.2 Economic decision making . . . . .  | 22          |
| 2.3 What's on the agent's mind? . . . . .   | 32          |
| 2.4 Critical transitions . . . . .  | 35          |
| 2.5 Dealing with uncertainty and high-impact . . . . .  | 37          |
| <b>3 The Energy Transition: A reliance on technology alone ultimately leads to a bet on Solar Fuels</b> | <b>41</b>   |
| 3.1 The choice at the heart of the energy transition . . . . .  | 43          |
| 3.2 Current and future energy demand . . . . .  | 44          |
| 3.3 Renewable electricity and electrification: immediate push to inevitable limits . . . . .            | 45          |
| 3.4 The orthodox energy transition for fuels: efficiency, bio-energy and offsets . . . . .              | 46          |
| 3.5 The technology leap: what one needs to believe for solar fuels . .                                  | 47          |
| 3.6 Conclusion . . . . .  | 50          |

|   |            |
|---|------------|
| <b>4 The influence of the energy transition on the significance of key energy metrics</b>   | <b>53</b>  |
| 4.1 Introduction . . . . .  | 55         |
| 4.2 The use of Total Primary Energy . . . . .   | 58         |
| 4.3 The use of Electricity Generation Capacity . . . . .  | 67         |
| 4.4 Reflection on findings and consequences for policy design . . . . .   | 69         |
| 4.5 Conclusion . . . . .  | 70         |
| <b>5 Jumping to a better world: An agent-based exploration of criticality in low-carbon energy transitions</b>                    | <b>73</b>  |
| 5.1 Introduction . . . . .  | 75         |
| 5.2 Critical transitions . . . . .  | 77         |
| 5.3 Methods . . . . .   | 81         |
| 5.4 Experiments & results . . . . .   | 85         |
| 5.5 Reflection on model results . . . . .   | 88         |
| 5.6 Reflection on modelling approach . . . . .  | 90         |
| 5.7 Conclusion . . . . .  | 94         |
| <b>6 Investment in the future electricity system - An agent-based modelling approach</b>  | <b>97</b>  |
| 6.1 Introduction . . . . .  | 99         |
| 6.2 Investment decisions in an evolving electricity system . . . . .  | 101        |
| 6.3 Conceptualisation . . . . .   | 104        |
| 6.4 Experimental setup and results . . . . .  | 109        |
| 6.5 Validation and discussion on model results . . . . .  | 117        |
| 6.6 Conclusion . . . . .  | 121        |
| <b>7 Why fully liberalised electricity markets will fail to meet deep decarbonisation targets even with strong carbon pricing</b> | <b>125</b> |
| 7.1 Introduction . . . . .  | 127        |
| 7.2 Background . . . . .  | 129        |
| 7.3 Methodology . . . . .   | 131        |
| 7.4 Experimental setup and hypotheses . . . . .   | 138        |
| 7.5 Results . . . . .   | 143        |
| 7.6 Discussion . . . . .  | 149        |
| 7.7 Conclusions and policy implications . . . . .   | 151        |
| <b>8 Conclusions, Recommendations &amp; Reflection</b>  | <b>155</b> |
| 8.1 Research context, focus and approach . . . . .  | 157        |
| 8.2 Conclusions . . . . .   | 159        |
| 8.3 Recommendations for policy makers . . . . .   | 162        |
| 8.4 Recommendations for business decision makers . . . . .  | 164        |
| 8.5 Reflection . . . . .  | 165        |

|                         |            |
|-------------------------|------------|
| <b>9 Samenvatting</b>   | <b>171</b> |
| <b>Acknowledgements</b> | <b>189</b> |
| <b>About the author</b> | <b>191</b> |
| <b>Publications</b>     | <b>193</b> |
| <b>Bibliography</b>     | <b>195</b> |



# List of Figures

|   |    |
|---|----|
| 1.1 A simple formula that summarises the challenge of mitigate climate change . . . . .                   | 4  |
| 1.2 World energy-related CO <sub>2</sub> -emissions . . . . .   | 7  |
| 2.1 Three systems . . . . .   | 22 |
| 2.2 A perspective on the energy transition . . . . .  | 24 |
| 2.3 Types of goods . . . . .  | 25 |
| 2.4 The tragedy of the commons . . . . .  | 25 |
| 2.5 A prisoner's dilemma . . . . .  | 26 |
| 2.6 Climate and welfare sensitivity . . . . .   | 30 |
| 2.7 Policy perspective matrix . . . . .   | 31 |
| 2.8 The concept of critical transitions . . . . .   | 36 |
| 2.9 A diagram differentiating applied science, professional consultancy and post-normal science . . . . . | 38 |
| 3.1 A paradigm for the two dimensions of progress in the energy transition . . . . .                      | 43 |
| 3.2 The five principal elements of solar fuels production . . . . .                                       | 48 |
| 3.3 Outline costs for solar fuels production . . . . .  | 49 |
| 4.1 Primary energy metrics and efficiency indicators . . . . .  | 58 |
| 4.2 Primary energy sources . . . . .  | 59 |
| 4.3 Total primary energy of Shell's Sky scenario under different accounting methods . . . . .             | 62 |
| 4.4 Total Primary Energy by selected country by accounting method . . . . .                               | 62 |
| 4.5 Energy Intensity by selected country by accounting method . . . . .                                   | 66 |
| 4.6 Relationship between investments, capacity factors and actual production. . . . .                     | 68 |
| 5.1 The catastrophe fold . . . . .  | 78 |

|      |   |     |
|------|---|-----|
| 5.2  | Model structure . . . . .   | 85  |
| 5.3  | Results of the ACT model . . . . .  | 86  |
| 5.4  | Summary of results and comparison with the Shell Scenarios . . .  | 90  |
| 5.5  | Learning by analogy . . . . .   | 93  |
| 6.1  | Model description . . . . .   | 105 |
| 6.2  | Decision-making process of investors. . . . .   | 106 |
| 6.3  | Relationship between scarcity rent and excess capacity factor . .   | 108 |
| 6.4  | Electricity production in percentage by resource with two carbon<br>price scenarios . . . . .               | 111 |
| 6.5  | Comparison between current study and two other scenario studies   | 114 |
| 6.6  | The effect of heterogeneity of investors on the electricity mix . . .                                       | 115 |
| 6.7  | Electricity mix with varying power generation from renewable<br>generation . . . . .                        | 116 |
| 6.8  | Three scenarios for the cost development of a renewable power<br>generation asset . . . . .                 | 117 |
| 6.9  | Electricity mix by source with varying technology learning curves   | 117 |
| 6.10 | The average discount rate of investors over time . . . . .  | 118 |
| 7.1  | Scarcity rent . . . . .   | 133 |
| 7.2  | Floor price . . . . .   | 134 |
| 7.3  | Scarcity rent and floor price development with increasing shares<br>of renewable power production . . . . . | 136 |
| 7.4  | Experiment-tree . . . . .   | 140 |
| 7.5  | Carbon price scenario . . . . .   | 143 |
| 7.6  | Results from experiments . . . . .  | 145 |
| 7.7  | Ideal energy - only market . . . . .  | 146 |
| 7.8  | Realistic energy-only market . . . . .  | 146 |
| 7.9  | Realistic market with CRM . . . . .   | 147 |
| 7.10 | Sensitivity to carbon price scenarios . . . . .   | 149 |

# List of Tables

|     |  |     |
|-----|--|-----|
| 1.1 | Research questions by chapter . . . . .  | 15  |
| 4.1 | Production efficiencies of non-combustible energy sources . . . . .                                  | 61  |
| 4.2 | Average capacity factors of renewable generators . . . . .   | 68  |
| 4.3 | Qualitative assessment of the effect of policy targets set in TPE<br>or related indicators . . . . . | 70  |
| 4.4 | Qualitative assessment of the effect of policy targets set in EGC .                                  | 70  |
| 5.1 | The relationship between the energy transition and elements with<br>which ACT was extended . . . . . | 83  |
| 5.2 | Application of mean-field model to the energy transition in ACT .                                    | 83  |
| 5.3 | Experimental design . . . . .  | 86  |
| 5.4 | Comparison between mean-field experiment and subsequent ex-<br>perimental results . . . . .          | 87  |
| 6.1 | Variables of parameters at initialisation . . . . .  | 110 |
| 6.2 | Comparison of scenarios of the Dutch Electricity system . . . . .                                    | 113 |
| 7.1 | Values of variables of parameters at initialisation . . . . .  | 144 |
| 8.1 | Research questions by chapter . . . . .  | 158 |
| 9.1 | Onderzoeks vragen per hoofdstuk . . . . .  | 174 |



# List of abbreviations

|              |   |
|--------------|---|
| <b>GHG</b>   | GreenHouse Gas                              |
| <b>ABM</b>   | Agent-Based Modelling                       |
| <b>BC</b>    | Base Case                                   |
| <b>BECCS</b> | Bio-Energy Carbon Capture and Sequestration |
| <b>CRM</b>   | Capacity Remuneration Mechanism             |
| <b>CCS</b>   | Carbon Capture and Sequestration            |
| <b>CPR</b>   | Common Pool Resource                        |
| <b>CAS</b>   | Complex Adaptive System                     |
| <b>CSP</b>   | Concentrated Solar Power                    |
| <b>DAC</b>   | Direct Air Capture                          |
| <b>DEM</b>   | Direct Equivalent Method                    |
| <b>EGC</b>   | Electricity Generation Capacity             |
| <b>EE</b>    | Energy Efficiency                           |
| <b>EI</b>    | Energy Intensity                            |
| <b>ES</b>    | Energy Service                              |
| <b>GHG</b>   | GreenHouse Gas                              |
| <b>GDP</b>   | Gross Domestic Product                      |
| <b>IEM</b>   | Incident Energy Method                      |
| <b>KISS</b>  | Keep it Descriptive S.                      |
| <b>KIDS</b>  | Keep it Simple S.                           |
| <b>KPI</b>   | Key Performance Indicators                  |
| <b>LtG</b>   | Limits to Growth                            |
| <b>MFA</b>   | Mean-Field approach                         |
| <b>NDC</b>   | National Determined Contributions           |
| <b>NPV</b>   | Net Present Value                           |
| <b>OPEC</b>  | OPerating EXPenses                          |
| <b>ODD</b>   | Overview, Design concepts, and Details      |
| <b>PSM</b>   | Partial Substitution Method                 |
| <b>PV</b>    | PhotoVoltaic                                |
| <b>PECM</b>  | Physical Energy Content Method              |
| <b>PNS</b>   | Post-Normal Science                         |
| <b>SRMC</b>  | Short Run Marginal Costs                    |
| <b>TFC</b>   | Total Final Consumption                     |
| <b>TPE</b>   | Total Primary Energy                        |
| <b>VOLL</b>  | Value Of Lost Load                          |

